Automotive LiDAR Technology for Space Applications - Executive Summary Report

Prepared by: Kevin O'Neill
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Introduction, state of the art, high level goals

In this activity PixQuanta has executed the design, the end-to-end manufacturing description and test plan required to fabricate its innovative photodiode sensors for LiDAR and 3D imaging. PixQuanta, in this contract from the European Space Agency, has fully described the steps necessary to develop its photodiode technology to the next stages, enabling a new era of low-cost, mass-manufacturable sensors ready for monolithic integration onto silicon readout-integrated circuits. By leveraging space applications with PixQuanta commercial target applications in Consumer 3D imaging and Automotive LiDAR, PixQuanta is positioned to provide a sensor technology for low-cost missions in low-earth orbit as well as high value missions in GEO. Space applications include in-orbit rendezvous, such as docking to the ISS, collision avoidance, debris identification, and attitude identification for landing onto unknown surfaces such as asteroids.

The Work Breakdown Structure (WBS) for this activity is show in Figure 1. The activity comprises of 3 Work Packages (WP) covering the design, manufacture, and test. Each WP concludes in the Preliminary Design Review, Test Readiness Review, and Detector Design Review.

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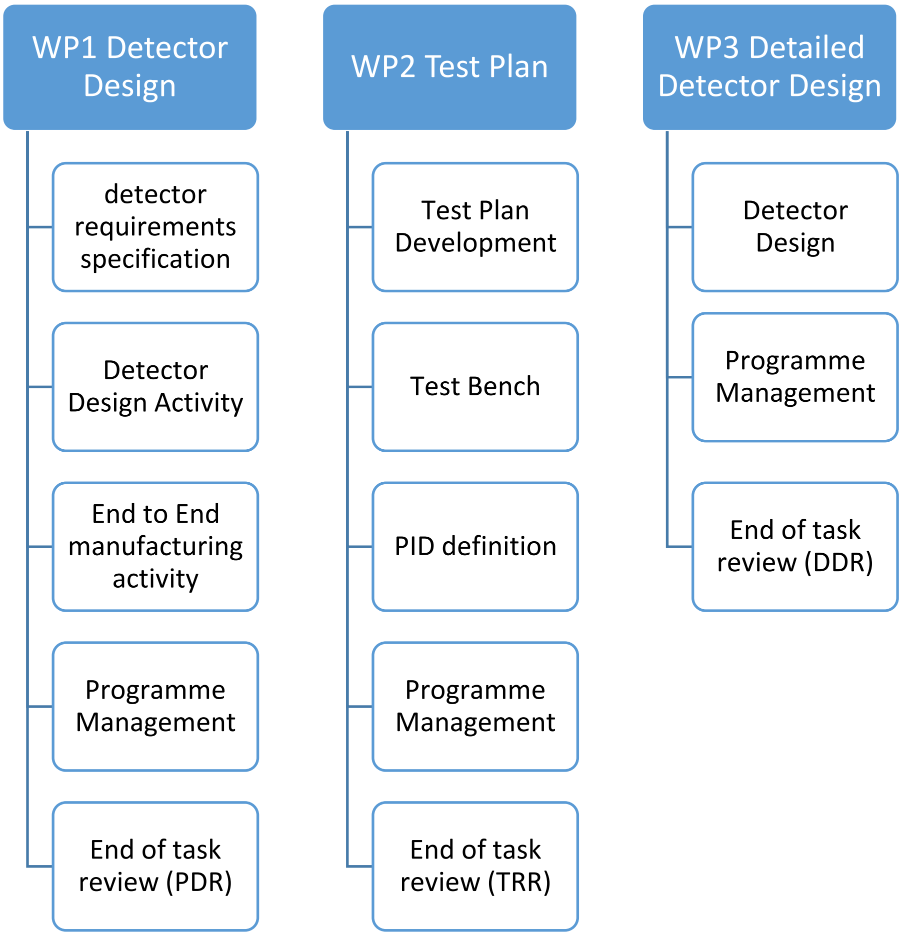

Figure 1: the Work Breakdown Structure for the project

The timing of this project is motivated by the recent commercial interest in LiDAR in the automotive market. For this reason, the LiDAR imaging market has seen rapid changes in recent years. Once a highly specialized niche technology for defence and geo-surveying applications, where an imaging LiDAR system might cost typically $100,000 or more and require the space of a cubic meter, the current 3D LiDAR systems being developed target a cost of $100 and can fit in the palm of a person's hand. The main commercial breakthrough for the recent surge in imaging LiDAR development is the proliferation of advanced driver assistance systems (ADAS) for the automotive market. Beyond increasing levels of ADAS the 'holy grail' for the car industry is to eventually create a driverless, or autonomous vehicle.

The reason for this interest in LiDAR through ADAS markets is the perceived sensor gap in this market. Mature sensor technologies exist for a variety of automotive use cases: ultrasound for short-range activities such as parking, radar for distance ranging over short, intermediate and long range for collision avoidance, and imaging sensors combined with machine learning for blind spot detection, lane tracking, and automatic cruise control. A shortcoming of the combination of ultrasound, radar, and image sensor is the absence of a combined imaging and distance ranging technology. Such a technology is needed to fuse the information provided by the existing sensing technologies and to resolve ambiguities generated by edge case scenarios.

The sensor gap opportunity is being answered by the development of 3D LiDAR systems, which have already begun to be commercialized in a mechanical scanning solution for the automotive market. In the longer term a pure solid-state solution is required to meet the reliability goals for this technology.

In addition, the need to reduce costs requires a high-volume production for 3D cameras, the main component in a LiDAR system, that can achieve single photon timing. For this reason, the most actively developed sensor technology for LiDAR solid state imaging is the silicon SPAD. SPADs provide a high gain combined with fast timing performance, and they are capable of monolithic integration for 3D LiDAR.

The detector requirements specification specifies the user needs and user requirements for a LiDAR sensor. The user in this case is a LiDAR systems manufacturer for Space applications which are closely aligned with automotive applications. The detector is a receiver subsystem of a LiDAR system which consists of a transmission and receiver part. A LiDAR system using CIS style ROIC for readout is shown diagrammatically in Figure 2.

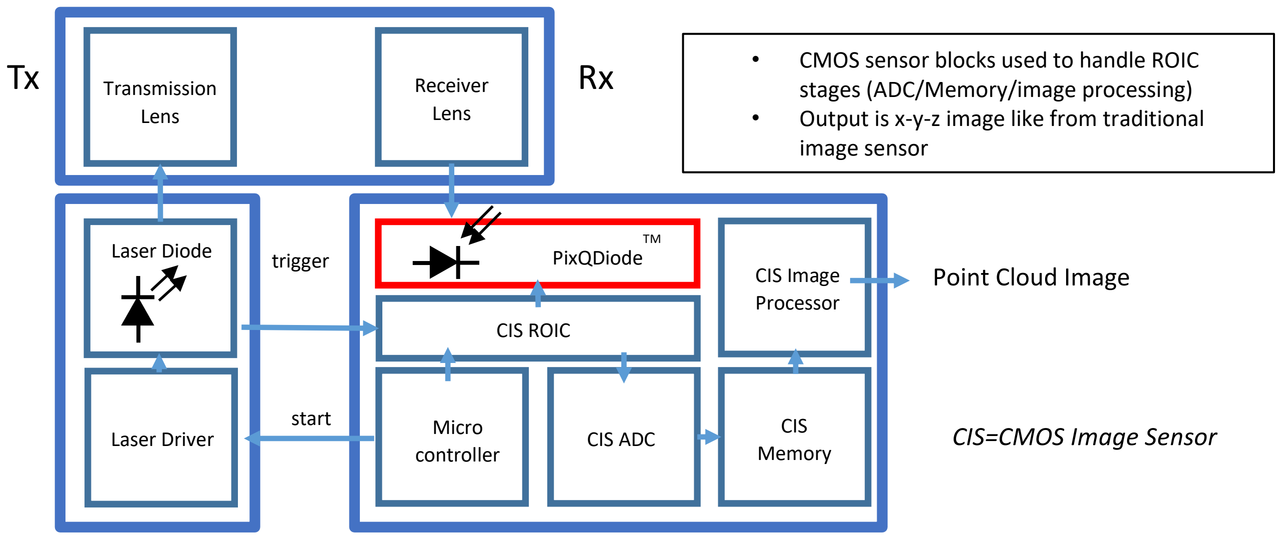

Figure 2: The LiDAR system concept as proposed, using a CMOS Image Sensor as the ROIC for a flash-LiDAR implementation

The relationship between the User Needs, User Requirements and System requirements are connected. The System requirements in turn are mapped to the technical requirements of the sensor layer and this is shown diagrammatically in Figure 3.

Advantages over this thin film APD technology of this project over the current silicon based sensor solution are listed in Table 1.

Table 1: advantages of the proposed thin film APD technology over the incumbent silicon SPAD technology

Specification	Silicon SPAD	PixQuanta thin film APD
Detection Efficiency at 905nm	6%	30%
Minimum Pixel Size	10µm	3µm
Excess Noise	20%	10%
Charge Gain	10^6	10^4
Excess noise	20%	10%

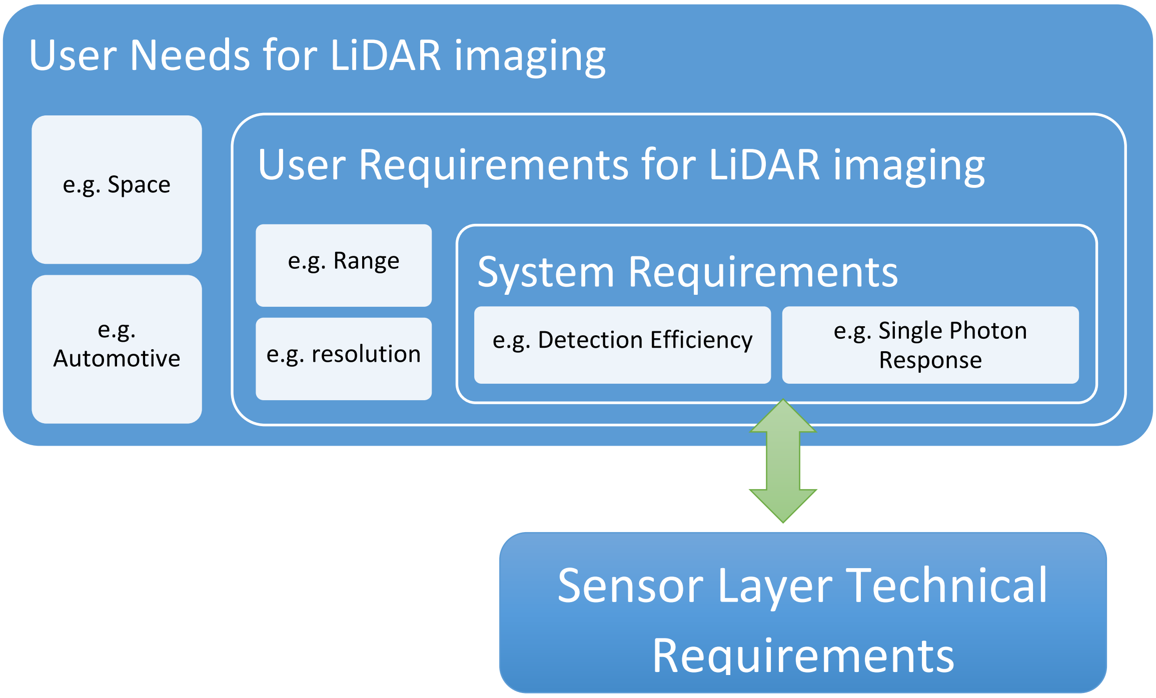

Figure 3: Relationship between User needs, user requirements, system requirements and technical requirement for the sensor in a LiDAR system

The goals of the activity are to produce a direct and indirect time-of-flight depth/3D sensor platform enabling the next generation of solid-state LiDAR solutions. The solution is potentially useful for automotive LiDAR market for advanced driver assistance systems (ADAS) and the consumer 3D market but could be adapted for use in space applications. Space applications cover various use cases, such as whether the remote object being visualized is known or unknown, the range of the given objects, the ambient light conditions, and the resolution (laterally in x and y as well as depth).

The technology development programme is designed to bring PixQuanta's photodiode technology closer to a final 3D LiDAR detector solution. The technology platform should be designed to interface on-chip with a ROIC to provide a monolithically integrated detector in x, y and distance. There is an additional opportunity to provide x,y and image intensity in the same technology, resulting in a combined 3D LiDAR and image sensing detector. The result is an all-solid state, reliable, low power, single component sensor with ultra-small footprint that can be integrated into a LiDAR module for multiple applications.

Developing this technology platform paves the way for a combined depth and imaging function in a single CMOS sensor. This approach combines mature low-cost manufacturing technologies to provide a pure solid-state solution for 3D flash LiDAR. Existing detector concepts are based on mechanical scanning, because of the fill-factor trade-off of integrating a sensor onto a readout pixel. In this project, and NIR sensor technology is developed to exceed the performance of incumbent silicon SPAD technologies in this wavelength range. In future projects, PixQuanta's thin film sensor platform could be modified to provide a similar sensor layer at SWIR wavelengths This would provide a LiDAR 3D sensor operating in the wavelength range 1300nm to 1600nm, mitigating concerns around eye safety and providing the opportunity to take advantage of atmospheric absorption bands that serve to block the effect of ambient background illumination at particular wavelengths such as 1310nm. While low cost SWIR VCSELs are not yet commercially available, it is likely that that they will become available in the coming 2 or 3 years, driven by the demand for longer range LiDARs.

Current Commercial Landscape for LiDAR Sensor Manufacture

There are two incumbent manufacturing technologies used to realise LiDAR receivers. The first is silicon CMOS that employs silicon-only manufacturing methods and can be scaled at low cost to high volume. Typical circuits integrate Silicon circuits with Single Photon Avalanche Detectors (SPADs) in combination with timing circuitry based on Time-to-Digital Conversion (TDCs). Both these technology blocks are available as standard to silicon designers in the Process Design Kits (PDKs) of major Silicon CMOS foundries such as Tower Jazz, TSMC, Japan Semiconductor (formerly Toshiba) etc.

Silicon CMOS is the most cost-effective way to make a reliable lidar sensor; in terms of performance, however, there is a critical shortcoming: there is an inherent issue with using silicon CMOS due to the wavelength restriction due to the material properties of silicon semiconductor. This means that sensitivity of silicon CMOS based devices can go no further than NIR wavelengths (up to 940nm), and typically have detection efficiencies in the single percent. Eye safety restrictions in NIR wavelength ranges reduce the amount of laser power that can be used and therefore exacerbates range performance. Furthermore, there is no way to extend the wavelength sensitivity to the SWIR range, as the material choice is fixed to crystalline silicon. Operation at SWIR wavelengths would benefit LiDAR applications to overcome challenges in performance in adverse weather conditions, such as rain, fog or sleet. Significant range performance improvement in SWIR vs NIR is possible due to the increased intensity made possible by the eye-safety requirements specific to this wavelength range.

The second incumbent technology is compound-semiconductor or III-V based manufacturing. This technology creates the material requirements for high infrared absorption, for example in photodiodes created from Indium Gallium Arsenide, and provides a LiDAR sensor solution with high performance in the NIR and SWIR wavelength ranges. While the performance meets the requirements, the challenge here is that the cost is very high due to the expense of processing compound III-V materials and the high cost of integration with silicon-based ROICs. Furthermore, the high noise of this particular kind of direct-bandgap sensor solution requires system level cooling approaches, which in turn add to the system-level cost of the detector.

To summarize the two main technologies described above, for high volume manufactured automotive lidar products, silicon CMOS manufacturing technology meets the cost requirement but not performance requirement while the III-V manufacture meets the performance requirement but not the cost requirement. The question is if there exists a silicon CMOS compatible sensor solution can provide low cost and match the high performance of a III-V technology. The answer lies in a mature manufacturing technology that is already developed for thin film photovoltaics, that can efficiently capture infra-red light using standard large-area thin film deposition techniques.

Definition of end-to-end manufacturing

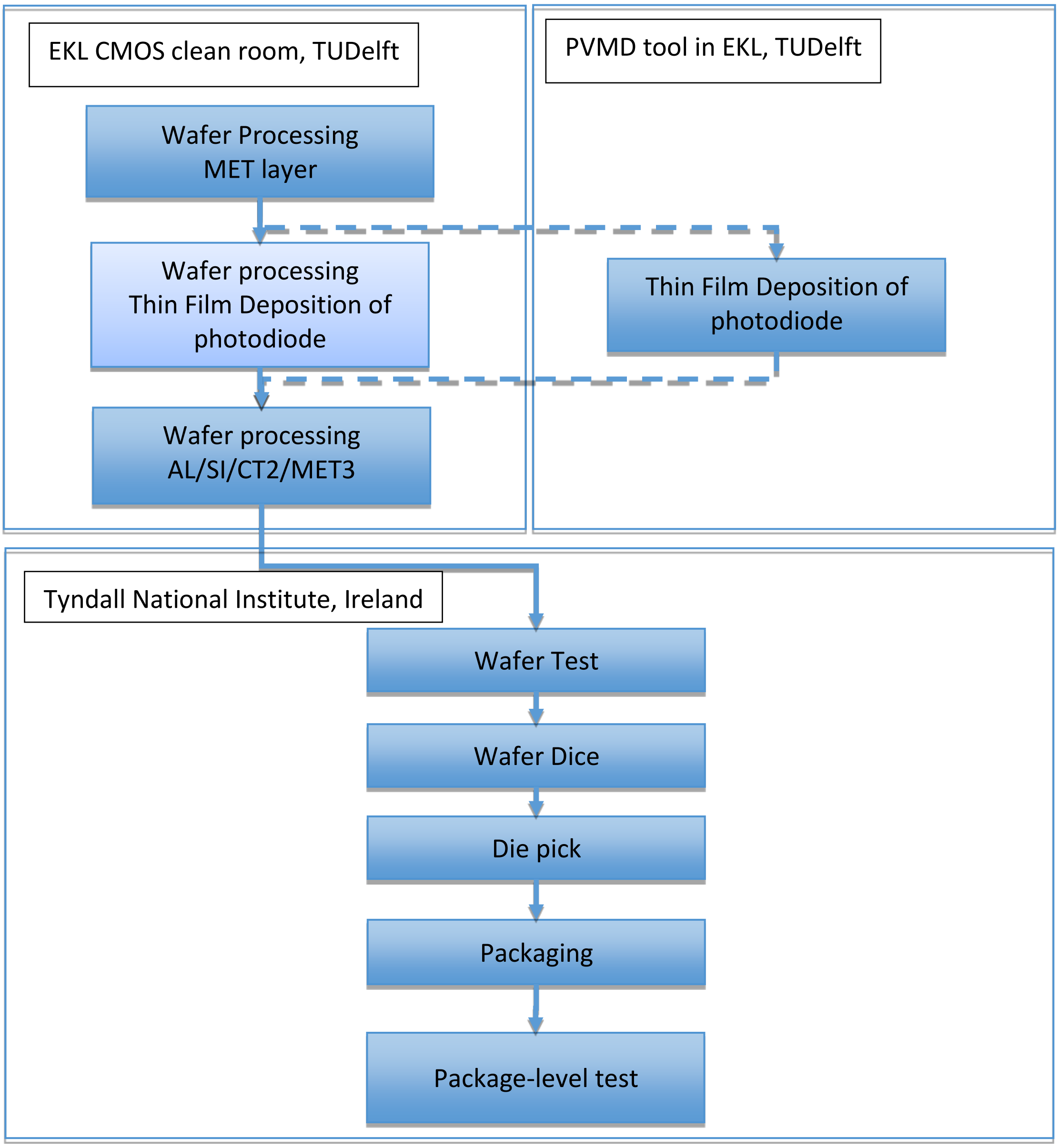

Figure 2: work flow of end-to-end manufacturing

The end-to-end manufacturing. To develop the process for the thin film sensor technology, PixQuanta's supplier is Else Kooi Laboratories (EKL) in partnership with the PVMD group in TUDelft. The director of EKL is Casper Juffermans and the head of the PVMD group is Olindo Isabella. PixQuanta and EKL have an agreement in place that allows PixQuanta employees access to the CMOS class 100 clean room for an agreed rate of €150/hour, which includes unlimited use of the tools in the lab. EKL operates a full silicon CMOS fab for a 100mm wafer line. This provides a convenient environment to develop CMOS processes at low volumes. All of the materials and tools are available at EKL to complete the fabrication of devices.

A second source for the tools available at EKL is available through the Tyndall Institute in Ireland. This allows the bulk of wafer fabrication to take place in Ireland and the wafer start at EKL in the Netherlands.

Designs of pixels, package for test

The design of the pixel is driven by the available ROICs for available monolithic integration, which is envisaged to be a future follow-on activity. Four candidate ROICs are listed in Table 1, together with the manufacturer(s) and array sizes. The manufacturers can provide the ROICs on 200mm wafers for direct processing of the subsequent sensor layer by PixQuanta.

Table 1: pixel sizes of commercially available ROICS

Pitch	**Target ROIC**	**Array size**
15µm	FLIR ISC 1202 Mikro-Tasarim imaging ROIC MT6415	640×512
25µm	FLIR ISC0002-1 Mikro-Tasarim imaging ROIC MT6425	640×512
55µm	ASI Timepix STPX-65k	256×256
75µm	Mikro Tasarim LiDAR (under development)	256×256

With the available wafer processing facilities at EKL, it is possible to create arrays with the pixel geometries described in Table 2. This table relates to the pixel sizes of the available ROICs shown in Table 1. EKL supports 100mm wafer fabrication, this will be made possible by resizing, or 'coring', the the ROIC wafers through a wafer dicing vendor.

Table 2: Overview of Pixel Designs proposed for the follow-on fabrication activity

Pixel pitch	Design rule	Active Area dimension	Area loss due to contact	Fill Factor
15µm	1µm (Mask Aligner)	13µm	20µm^2	66%
25µm	1µm (Mask Aligner)	23µm	20µm^2	81%
55µm	1µm (Mask Aligner)	53µm	20µm^2	92%
75µm	1µm (Mask Aligner)	73µm	20µm^2	94%

The corresponding die design which incorporates all four pixel designs in shown in Figure 3, and is proposed as the test chip for the follow-on fabrication activity.

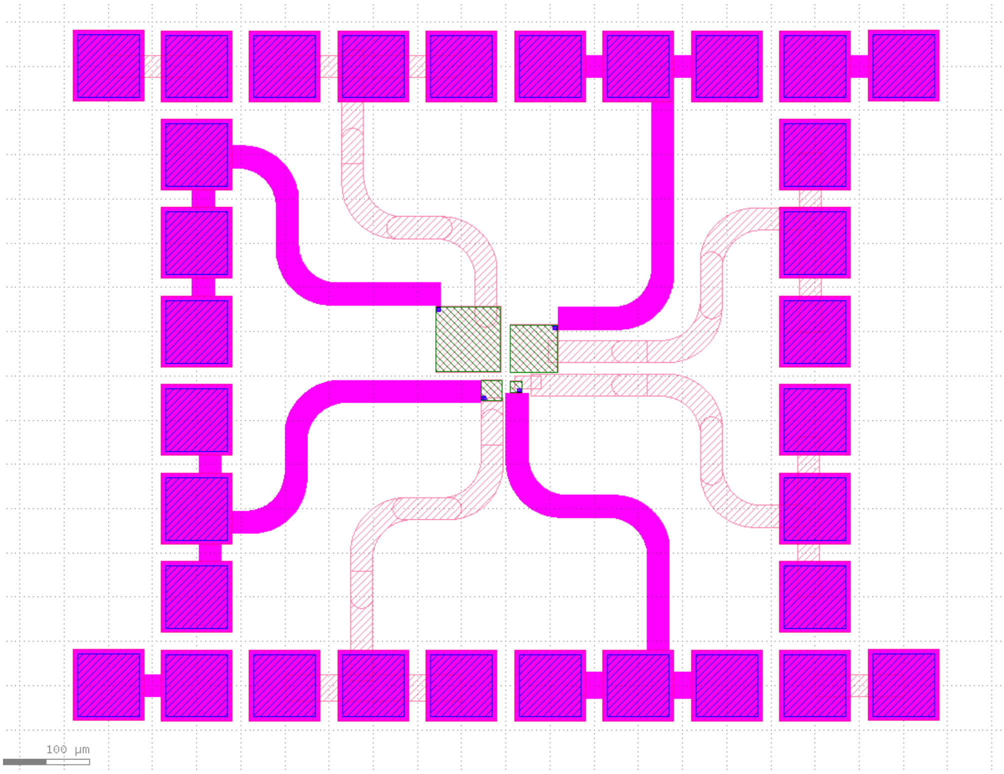

Figure 3: proposed single pixel test chip design incorporating four different pixel designs

The die package design chosen for this project is a windowed TO18 can available from Schott. The package cross section diagram is presented in Figure 4. The advantage of this design is compatibility with existing commercially available packaged products which allow potential customers to easily incorporate PixQuantas device with minimal redesign.

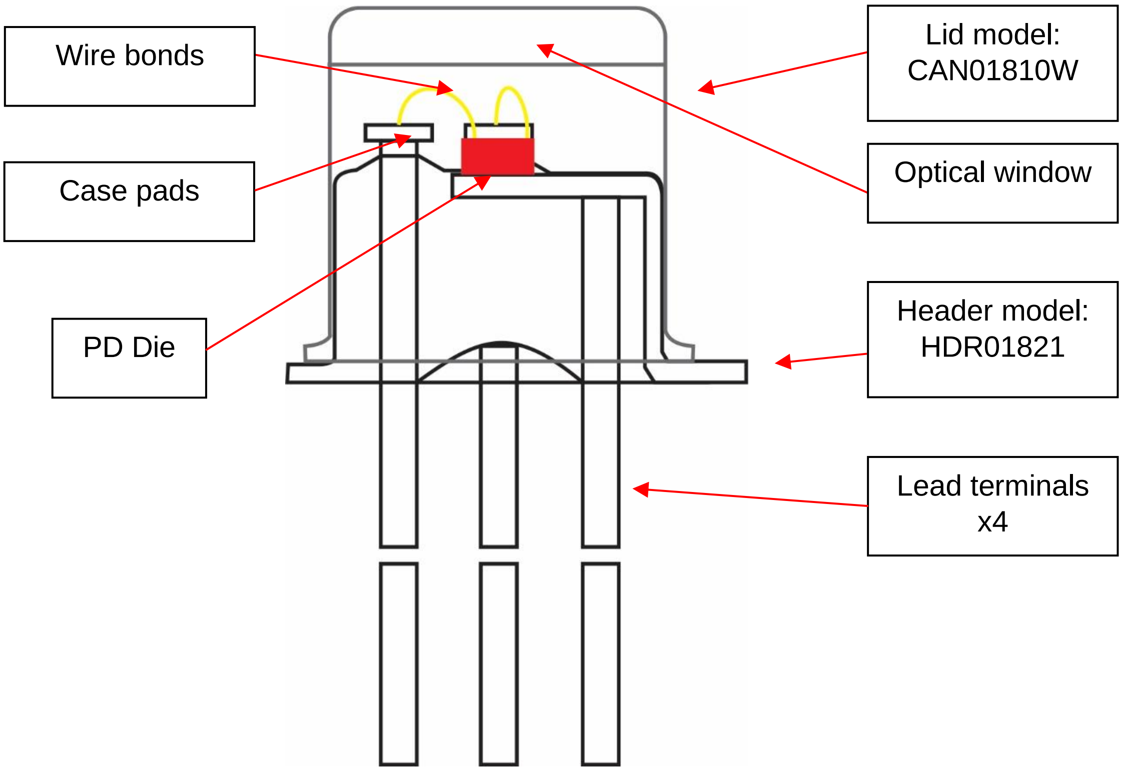

Figure 4: Cross section of TO18 package assembly

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Test frameworks

Test frameworks were established for the test plan development and test bench verification activity. The test plan includes wafer and part level tests as well as future improvements and requirements for PixQuanta's test devices. In this activity, every procedure for electrical, electro-optical or environmental test/measurements is designed to be self-contained, for later use as a SOP for testing. The SOPs each comprised of the following subsections:

- Introduction
- Setup description
- Tools used during the procedure
- definition of parameters
- The actual procedure (example: IV measurement or Total ionising dose)
- Outputs

The wafer test comprises of the following measurements:

- Current-Voltage (IV) measurements on wafer
- Capacitance-Voltage (CV) measurements
- Responsivity / Quantum efficiency measurements

The wafer measurements are available at the Tyndall National Institute in Cork, Ireland. PixQuanta has access agreements in place for PixQuanta employees to use the Cascade Wafer probe tool and a Bentham TM300 Quantum Efficiency test station.

The part test comprises of the following measurements:

- Current-Voltage (IV) measurements on parts
- Capacitance-Voltage (CV) measurements on part level
- Timing response measurements on part level
- Excess noise measurements on part level, introduction

The environmental tests to be carried out on parts will include:

- Thermal Cycling
- Humidity Test
- Total Ionizing Dose
- Proton Irradiation

PixQuanta will test its devices for Thermal Cycling and Humidity Test at the Tyndall National Institute. The Total Ionizing Dose will be performed at ESA-ESTEC in the Netherlands, and the proton irradiation will take place in University of Liege, in Belgium.